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# A VOLUME REGULATOR FOR BLAST-FURNACE ENGINES

BY

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# A VOLUME REGULATOR FOR BLAST-FURNACE ENGINES

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*Blast-furnace operation has attained a high degree of refinement in the proportioning of the various materials composing the charge — the ore, the fuel and the flux. The weight of oxygen — introduced as atmospheric air — per charge has, however, until recently been subject to much uncertainty due primarily to the difficulty of measuring with any degree of accuracy the volume of air delivered. The adjustment of the air supply to the furnace was, therefore, usually made only when the operator found evidence that the furnace was badly overblown or underblown, a process which resulted in a more-or-less variable product and certainly in a reduction in the possible maximum output of the furnace.*

*With the advent of the centrifugal compressor giving a perfectly steady air blast, the metering of the air supply became more practical and, therefore, more usual. With perfectly definite and uniform charging a definite and uniform* weight *of air per minute is desirable. Constant-volume governors have been designed on two principles, one by metering the air by means of a venturi meter and the other by using an impact float. The venturi-meter governing has been improved by using a multiple venturi meter in which large pressure drop can be obtained in the throat without a corresponding loss in power. This difference in pressure is used on a mercury pot whose motion up and down is translated to the governing mechanism of the driver of the air compressor. The proper setting of this meter is accomplished by changing the tension of the spring until a scale calibrated in cubic feet of air per minute shows that the desired quantity of air is obtained.*

*In the impact float method the air is taken through a conical opening in which is suspended a float, this float moving a horizontal beam about a pivot. The horizontal beam actuates the governing mechanism of the driver of the air compressor. On this horizontal beam is a sliding weight which can be set at calibrated marks representing cubic feet of free air per minute. With the weight set in a definite position a certain definite quantity of air is obtained.*

*In both of these methods, however, the readings on the calibrated scale are only correct when the initial air conditions are standard, that is, are similar in barometer, temperature and humidity to which the scale has been calibrated. Any change in either the temperature of the inlet air or in the atmospheric barometer or in the humidity of the air, changes the weight of the air metered, and, therefore, its oxygen content. As the blast furnace requires an exact weight of oxygen, the above method*

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*of holding constant volume is liable, in extreme cases, to have an error of from 15 to 20 per cent.*

*A volume corrector is herewith presented which when used in connection with the air-metering device will correct for any changes in either temperature, barometer and humidity, so that the air supplied to a blast furnace will, at all times, under any atmospheric conditions, deliver a perfectly definite and predetermined weight of oxygen to the blast furnace. This volume corrector is so designed that it requires only one setting for each correction, that is, one setting for any initial temperature, one setting for any existing barometer and one setting for humidity as usually obtained by the difference of readings on a wet- and dry-bulb thermometer.*

THE proper regulation of the quantity of air supplied to a blast furnace deserves careful study, the results aimed at being a more uniform quality of product and a greater output per furnace. The latter feature, while always very valuable, assumes especial importance during these war times. But, before considering the problem of regulation, it might be well to state in very simple terms the primary function of a blast furnace.

## FUNCTIONS OF A BLAST FURNACE

2 The blast furnace is primarily an apparatus for producing pig iron; but incidentally it may also be regarded as a huge gas producer. The materials fed to it are the iron ore, the fuel (coke), and the fluxes (limestone), which are charged at the top of the furnace or throat; and the air blast, which is blown in near the bottom of the furnace at the tuyeres. The materials discharged from the furnace are pig iron and slag, which are tapped from the bottom or crucible of the furnace, and the gases and dust, which pass out of the top of the furnace. The iron ore in a blast furnace is deoxidized or reduced, for which purpose the furnace is charged with sufficient carbonaceous fuel to do two things: To abstract all the oxygen from the reducible metallic oxides and to furnish enough heat at high enough temperature to melt down to superheated liquids the pig iron and slag, — combinations of irreducible metallic oxides, — that are formed. The fuel must supply the reducing energy and the melting-down or smelting requirements; the first by action upon the metallic oxides at a red to a white heat and abstracting their oxygen; the second by being burned at the foot of the furnace by the hot-air blast, and there generating the heat and higher temperatures necessary for the smelting down of the materials already reduced.

3 In a secondary way the blast furnace may also be regarded as a huge gas producer, run by hot forced blast, in which the incombustible portions of the contents are melted down (with a little un-

burnt carbon) to liquid metal and slag, and are run out beneath, while the gaseous products pass upwards through 50 to 100 ft. of burden, and escape above. The escaping gases are primarily of the composition of producer gas, with some of its carbonous oxide changed to $CO_2$ by the oxygen abstracted from the burden; with some $CO_2$ added from the decomposition of the carbonates of the charge: and with the usual increment of moisture from the charge and volatile matter (if any) from the distillation of the fuel. Hence, the blast furnace is a huge gas producer, giving a rather inferior quality of combustible gas in large quantities, while reducing to metal and slag the burden of iron ore and flux (limestone) which is put in with the fuel. In fact, the unoxidized and combustible ingredients of the escaping gas represent a large part, often the largest part, of the total calorific power of the fuel.

## AIR REQUIREMENTS IN BLAST FURNACES

4 From the above it can be readily seen that if the charging of a furnace is uniform it is quite essential to have the amount of air supplied to the furnace also uniform in quantity. The air pressure required for forcing the air through the furnace varies with the condition of the burden or charge. If the particles of ore, fuel, and limestone are large, that is, the spaces between these particles ample, there is a freer passage for the air than if the particles of ore, fuel, and limestone are small and closely packed. Under certain conditions the furnace may require a pressure of say 10 to 15 lb. to force a certain quantity of air through it, while under other conditions, when the material in the furnace is tightly packed, a much higher pressure, sometimes as high as 25 to 30 lb., is required to force through the same amount of air.

## AIR COMPRESSORS FOR BLAST FURNACES

5 It is therefore absolutely necessary that the air compressor be capable of adapting itself automatically to supply a predetermined *weight* of air, corresponding to the charge in the furnace, regardless of the resistance encountered up to a certain prescribed maximum. Usually, the limiting air pressure is 30 lb., as this is the maximum pressure the stack itself will withstand with safety.

6 The expression *weight of air* is used advisedly, because the blast furnace requires a definite weight of oxygen to combine with the carbon in the coke charged to the furnace. In general practice we refer to this definite weight of air (or oxygen) as a "constant volume

of air," but this volume must have reference to specific conditions of temperature, barometer and humidity, because any variation of these conditions changes the weight of oxygen contained in a given volume. The standard conditions most commonly referred to are dry air at 60 deg. fahr. temperature and 30 in. barometer. Air under these specified conditions contains, of course, a perfectly definite weight of oxygen per cubic foot.

## RECIPROCATING ENGINES AND BLOWERS

7 Up to the advent of the centrifugal compressor, reciprocating compressors were chiefly used for blast-furnace work. The governor of the compressor driver was set to maintain a speed corresponding to the desired quantity of air, the general idea being that each stroke of the compressor represented a practically constant quantity of atmospheric air regardless of the discharge pressure. A little reflection will show, however, that, at the end of the discharge stroke, the clearance space is full of high-pressure air, which must expand to atmospheric pressure on the return stroke before fresh air from the outside can be admitted. Now, assuming equal temperatures, the volume of a given weight of air is inversely proportional to the absolute pressure. So that with a clearance space of, say, 7 per cent and a discharge pressure of, say, 10 lb. per sq. in. gage or 24.7 lb. per sq. in. absolute, the air in the clearance space must expand $\frac{24.7}{14.7} \times 7$ or 11.8 per cent of the cylinder contents before fresh air can be admitted into the cylinder on the return stroke of the piston; while with a discharge pressure of 30 lb. gage or 44.7 lb. absolute, the air in the clearance space must expand to $\frac{44.7}{14.7} \times 7$ or 21.3 per cent of the cylinder contents before atmospheric air can be admitted. The useful travel of the piston is therefore reduced from 88.2 per cent of the cylinder contents to only 78.7 per cent. Then higher pressures mean higher final temperatures; and as the incoming air is heated by the clearance-space air and by the cylinder walls, a smaller weight of atmospheric air is admitted for a given travel of piston. Finally, higher pressures result in greater leakage by the piston rings from the high-pressure to the low-pressure end, thus further lowering the quantity of air admitted. These various influences greatly reduce the volumetric efficiency of a reciprocating compressor when operating at a constant r.p.m. against increased pressures.

8 The r.p.m. of the reciprocating compressor being thus but a

poor guide as to the weight of air supplied, it was left to the judgment of the blast-furnace operator as to whether or not the furnace was receiving the proper amount of air. If in his opinion the furnace was receiving too little air, that is, if it was underblown due to the charge in the furnace offering more resistance to air flow than previously, he would call for a higher speed of the reciprocating compressor. Speeding up the driver would then furnish a somewhat greater quantity of air at the higher pressure. If, however, the blast furnace was overblown, the reciprocating compressor was slowed down, and the quantity of air furnished was reduced. This method of operating, however, necessitated a decided change of condition in the furnace before the furnace operator knew that the air supply to the furnace was not correct, and in many cases the furnace got into a very poor condition before the operator changed the air supply and improved conditions.

9 With the gradual introduction of greater refinements in determining the quantities and the chemical composition of the ore, fuel and flux entering each charge in the blast furnace, the uncertainty in the quantity of air supplied began to stand out more and more as the weakest link in the chain. There was not only the need for a reliable method for measuring the quantity of air, but engineers were asking for apparatus which, while metering the air, would also automatically maintain constant any desired quantity, regardless of the furnace conditions. Before entering, however, into a discussion of the commercial methods for regulating the supply of air to a blast furnace, it may be advisable to review briefly the underlying theory and the more usual methods of measuring air in general.

## THEORY AND FORMULÆ FOR FLOW OF GASES

10 If a gas, such as air, is allowed to flow from a region of higher pressure to one of lower pressure, the velocity attained by the gas is a definite function of the difference of pressures of the two regions. Expressed mathematically,

$$V^2 = 2g \int_{P_2}^{P_1} \frac{dP}{\gamma} \quad \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where

$V$ = spouting velocity in ft. per sec.
$g$ = acceleration of gravity, 32.16 ft. per sec. per sec.
$P_1$ = initial (high region) pressure in lb. per sq. ft.
$P_2$ = final (low region) pressure in lb. per sq. ft.
$\gamma$ = local density of gas in lb. per cu. ft.

For an incompressible fluid, in which $\gamma$ is independent of the pressure, the above equation becomes

$$V^2 = 2g\frac{P_1 - P_2}{\gamma} \quad \ldots\ldots\ldots\ldots\ldots\ldots [1a]$$

11 If the flow takes place adiabatically, that is, so that the heat changes taking place in the gas during the flow are due wholly to the pressure changes in the gas and to no other cause whatever, then

$$\frac{P_1}{\gamma_1{}^K} = \frac{P_2}{\gamma_2{}^K} \quad \ldots\ldots\ldots\ldots\ldots\ldots [1b]$$

where $K$ is the ratio of the specific heat at constant pressure to the specific heat at constant volume for the particular gas. Equation [1] thus becomes:

$$V^2 = 2g\frac{K}{K-1}\frac{P_1}{\gamma_1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right] \quad \ldots\ldots\ldots\ldots [2]$$

12 If this spouting velocity takes place through an orifice of $A$ sq. ft. having a velocity coefficient $f$ (determined experimentally), the discharge $W$ in lb. per sec. is:

$$W = fA_2\gamma_2\sqrt{2g\frac{K}{K-1}\frac{P_1}{\gamma_1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right]}$$

or

$$W = fA_2\sqrt{2g\frac{K}{K-1}P_1\,\gamma_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{K}} - \left(\frac{P_2}{P_1}\right)^{\frac{K+1}{K}}\right]}$$

or

$$W = fA_2\sqrt{2g\gamma_1\frac{K}{K-1}}\sqrt{P_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{K}} - \left(\frac{P_2}{P_1}\right)^{\frac{K+1}{K}}\right]} \quad \ldots\ldots [3]$$

13 For Eq. [3] two cases must be distinguished: First, when $\frac{P_2}{P_1}$ is above a certain critical value (about 0.53 for air and 0.58 for steam), in which case the flow depends both on $P_1$ and on $P_2$ as per Eq. [3]; and secondly, when $\frac{P_2}{P_1}$ is below the critical value, in which case the flow is independent of the actual value of $P_2$ but is determined by a pressure $P_c$ which automatically establishes itself in the

throat (real or virtual) of the discharging orifice or nozzle. $P_c$ is given by the relation

$$\frac{P_c}{P_1} = \left(\frac{2}{K-1}\right)^{\frac{K}{K-1}} \quad \text{.....[3a]}$$

which, substituted in Eq. [3] gives:

$$W = fA_c\gamma_c\sqrt{2g\frac{K}{K+1}\frac{P_1}{\gamma_1}}$$

or

$$W = fA_c\sqrt{2g\frac{K}{K+1}P_c\gamma_1} \quad \text{.....[3b]}$$

where $A_c$ is the area of the throat or least section.

14 For practical computation work, the weight of the gas is expressed not in pounds but in cubic feet per second, at certain standard conditions (usually 14.70 lb. per sq. in. absolute and 60 deg. fahr.), and the exponential quantities

$$\left(\frac{P_2}{P_1}\right)^{\frac{2}{K}} \quad \text{and} \quad \left(\frac{P_2}{P_1}\right)^{\frac{K+1}{K}}$$

are each expanded in a series of terms. Eqs. [3] and [3*b*] are then written respectively as

$$Q = fa\frac{3.97}{\sqrt{T_1\gamma_0}}\sqrt{p_2(p_1-p_2) - \left(\frac{1.5}{K}-1\right)\left(p_1-p_2\right)^2} \quad \text{.....[4]}$$

and

$$Q = fap_1\frac{3.97}{\sqrt{T_1\gamma_0}}\sqrt{\frac{K}{K+1}\left(\frac{2}{K+1}\right)^{\frac{2}{K-1}}} \quad \text{.....[4a]}$$

where

$Q$ = cu. ft. of standard gas per sec.
$a$ = area of orifice in sq. in.
$T_1$ = initial (high-pressure region) temperature in. deg. fahr., abs.
$p_1$ = initial pressure in lb. per sq. in., abs.
$p_2$ = final pressure in lb. per sq. in., abs.
$\gamma_0$ = density at 14.70 lb. per sq. in. and 60 deg. fahr. in lb. per cu. ft.

15 For air [4] and [4*a*] become respectively

$$Q = fa\frac{14.52}{\sqrt{T_1}}\sqrt{p_2(p_1-p_2) - 0.0665(p_1-p_2)^2} \quad \text{.....[5]}$$

and

$$Q = fap_1\frac{6.98}{\sqrt{T_1}} \quad \text{.....[5a]}$$

16 The velocity of the air can at any point in the path be easily reconverted into a pressure which is equal to the difference of pressure producing this velocity and is therefore proportional to the $\gamma V^2$ at the particular point. This pressure is usually measured by a column of water or of mercury; or, if it is too large, it is measured directly in lb. per sq. in. The use of a pressure gage, however, is not recommended, as such gages are usually inaccurate in spite of frequent calibrations. It is much preferable to use a dead-weight gage arrangement as shown in Figs. 1*a* and 1*b*. The pipe or tubing brought from

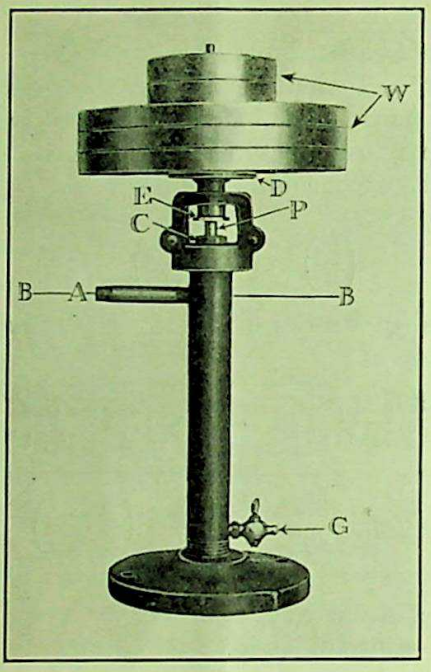


FIG. 1*a* USUAL TYPE OF DEAD-WEIGHT PRESSURE GAGE

the point where pressure is to be measured (in an air or steam main, for instance) is connected to pipe *A* which leads into a chamber filled with oil up to the level *B*-*B'*. A piston *P* (usually having an area of $\frac{1}{8}$ sq. in.) fits snugly into a tube *C* and carries a disk *D*. Weights *W* are placed on *D* until the air or steam pressure is correctly balanced, which is shown by the disk floating easily. To insure against sticking, the disk is constantly rotated, and to insure against having the piston lifted entirely out of the tube, collar *E* is provided, which prevents lifting the disk higher than the yoke above the collar. The photo-

graph of a similar dead-weight tester shows the older method of design. In the old design the pressure was admitted by a pipe shown extending horizontally from a vertical tube. The latter is filled with oil. The weights, disk, piston, and tube are similar in design as shown in Fig. 1*b*. The difficulty with the old design as shown in the photograph is that water of condensation quickly fills the oil reservoir, drives the oil out by leakage and finally leaves nothing but water in place of oil. In the new design shown in Fig. 1*b*, if there is

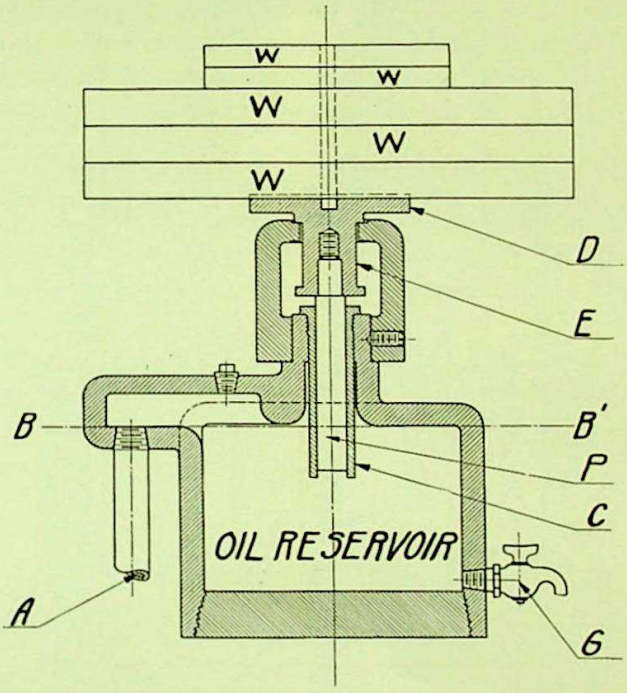


FIG. 1*b* IMPROVED TYPE OF DEAD-WEIGHT PRESSURE GAGE

any water introduced to pipe *A*, it will settle into the bottom of the reservoir and can be drained out through the cock *G*. The reason the inlet pipe *A* in Fig. 1*b* and the horizontal inlet pipe shown in the photograph are carried up to the level as indicated is to insure that the pressure measured is considered from the level *B*-*B'* which is the level of the oil under pressure. This is important when measuring small amounts of pressure, as a difference in the height of the location of the dead-weight gage adds or subtracts such distance from the small pressure to be recorded.

### COMMERCIAL METHODS FOR MEASURING AIR

17 The commercial methods for measuring air most commonly employed are: (1) The Receiver Method, (2) The Orifice Method, (3) The Pitot Tube, (4) The Venturi Meter, and (5) The Impact Float Method. Of these the first two methods waste the air they pass, and are therefore suitable only for temporary testing purposes. The other methods allow the air to pass to destination, and may therefore be left continuously in the system.

### RECEIVER METHOD

18 In the Receiver Method, the compressed air is passed into a closed system consisting of a tank and piping of known dimensions and full originally of air of atmospheric pressure and temperature,

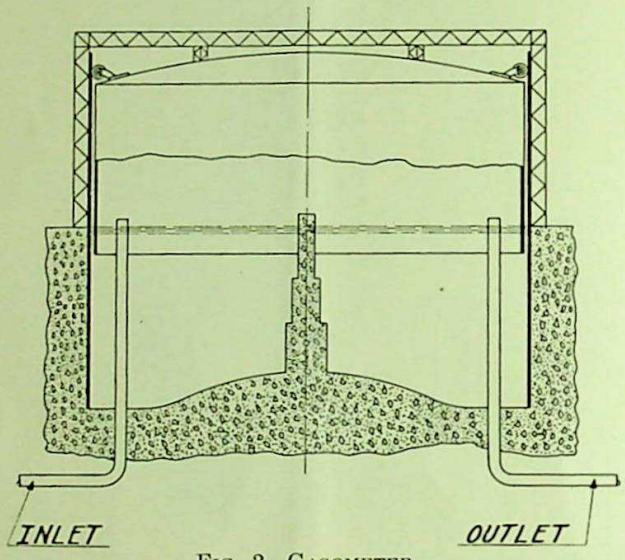


FIG. 2 GASOMETER
Can be used as a receiver for metering air

which conditions are taken as standard. After the compressed air has been flowing into the system for a sufficiently long period, say, half an hour or an hour, the pressure and the temperature are again observed. If the cubic contents of the system is $V$ cu. ft. and the standard or original absolute pressure and absolute temperature are $P_0$ and $T_0$ respectively, and the final conditions are $P$ and $T$, the final volume in the system referred to standard conditions is $V\frac{PT_0}{P_0T}$ cu. ft., and the inflow is $V\left(\frac{PT_0}{P_0T}-1\right)$ cu. ft. of standard air.

19 A tank as shown in Fig. 2 (similar to a large gas container) may also be used. The entering air raises the bell against gravity and atmospheric pressure, so that the pressure of the air in the tank is perfectly definite; and the volume can be read off directly from the rise of the bell after sufficient time has been allowed for the air to come down to atmospheric temperature.

20 The chief advantage of this method is that the measurement of the air is definite and is entirely independent of any coefficients. Its principal use is in connection with the calibration of orifices and the determination of the volumetric efficiency of very small reciprocating compressors. Evidently the measurement of the flow from a blast-furnace compressor would require a receiver system of entirely unwieldly and impractical dimensions.

## ORIFICE METHOD

21 In the Orifice Method the compressed air is allowed to discharge into the atmosphere through an orifice of known area and known velocity coefficient. The temperature $T_1$ is measured by

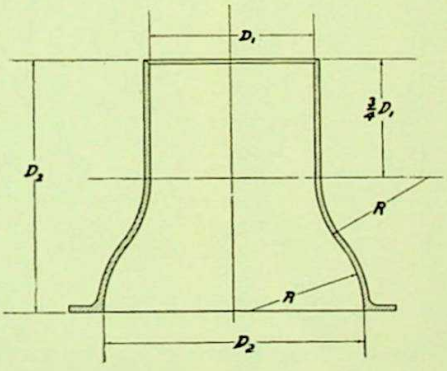


FIG. 3 STANDARD ORIFICE

Proper proportions are given, and for orifice diameters of one-half to one-third of the diameter of the air-discharge piping, coefficient of flow is very nearly 0.99

means of a bare thermometer inserted through the wall of pipe immediately preceding the orifice without well or casing of any kind. The type of orifice ordinarily used is the kind for which Equation [5] applies; that is, an orifice which is correct for a final pressure above the critical pressure. Such an orifice is theoretically wholly convergent, and it may stop with the smallest section attained. Practically, however, it is desirable to attach a parallel section of appreci-

able length to the end of the orifice, as shown in Fig. 3, to guide the air in parallel straight lines and thereby insure that the jet of air has the same diameter as the orifice end; in other words, that there is no *vena contracta* effect at the exit end of the orifice.

22 While the pressures $p_1$ and $p_2$ may, of course, be observed independently, it is preferable to observe the pressure drop $p_1 - p_2$ by means of an impact tube connected to an ordinary U-tube as shown in Fig. 4*a*. The impact tube is held in the center of the jet at a distance from the plane of the orifice equal to about $\frac{1}{3}$ of the orifice diameter. The difference of level in the U-tube is a correct

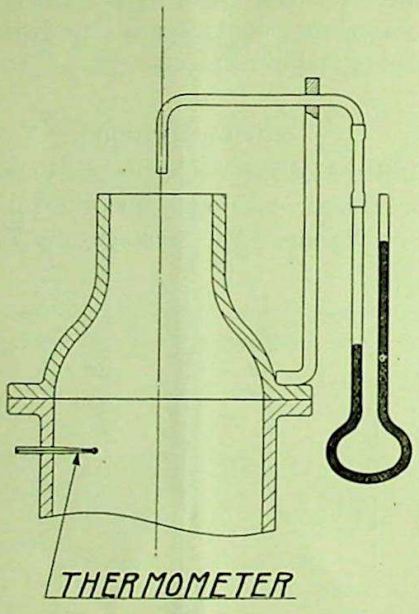


FIG. 4*a* IMPACT TUBE MOUNTED ON STANDARD ORIFICE

measure of the velocity head of the jet, since the static pressure of the jet is atmospheric. In other words, the full discharge pressure, if so desired, may be converted into velocity energy at the orifice end and then reconverted by the impact tube into the original pressure. The readings of the impact tube can, therefore, be made as large as desired; and even when measuring air flow from a compressor delivering a very low pressure, good readings on a water U-tube can be obtained. Fig. 4*b* shows the orifice in Fig. 4*a* mounted on a length of air-discharge piping for test purposes. During a compressor test, power readings are generally taken for a large number of loads and

quick and accurate readings on the impact U-tube by the use of the ordinary yardstick or rule are difficult, especially if the mercury or water column is oscillating somewhat.

23 For such cases the use of the U-tube illustrated in Figs. 5 and 6 is strongly recommended. On the four-grooved board the U-tube is supported in the two outer grooves and two properly shaped metal pointers slide easily in the inner grooves. To one of these

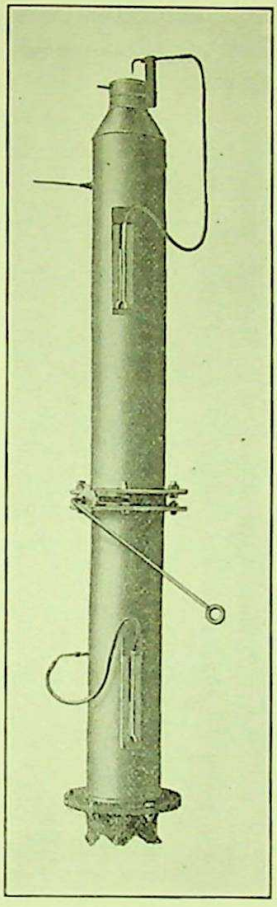

FIG. 4-*b* ORIFICE WITH IMPACT TUBE[1]

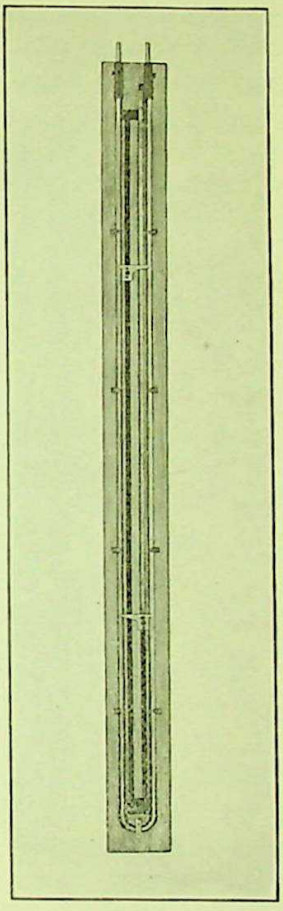

FIG. 5 IMPROVED TYPE OF U-TUBE[2]

[1] Shown mounted on air, discharge pipe as used in test.

[2] The steel scale with proper pointers can be set at the fluid levels and distance between pointers read directly on steel scale. Especially convenient for measuring slightly oscillating fluid levels.

pointers a graduated steel scale is attached, the zero on the scale starting at the pointer, so that this pointer is used for the lower level on the U-tube. The steel scale is kept taut by being counterweighted over a roller at the top of the board. The other pointer passing across the steel scale is set for the upper level, and thereby reads on the scale the difference in levels. By the use of this apparatus the observer is enabled to set the pointers at their respective levels at any time previous to the stated time for taking readings and he can keep

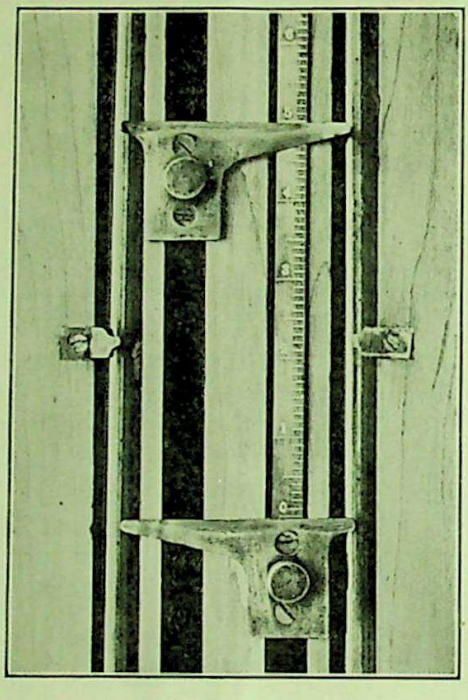

FIG. 6 ENLARGED VIEW OF SCALE AND POINTERS FOR U-TUBE IN FIG. 5

these pointers set continuously at the lower and upper levels on the U-tube. As soon as any change of these levels occurs the observer can instantly make a corresponding change of the pointers. This leaves him free at the instant of taking the readings to observe simply if the pointers are indicating correctly the lower and upper levels of the U-tube, or their mean levels if the liquid in the U-tube is oscillating. He can then read the length between the two pointers at his leisure. This is a great deal more convenient than having to set

at the instant the reading must be taken, one end of the measuring stick at the lower level of the U-tube, and quickly catch the reading of the upper level on this scale.

24 An observer manipulating a long measuring stick close up to the U-tube cannot possibly observe both the lower and upper levels quickly and take a reliable numerical reading; whereas with the device described above he can stand away from the instrument and take an instantaneous check by observing if both pointers stand correctly at the proper levels. Instead of a continuous glass U-tube, which is rather expensive and easily liable to break in transportation and by jars, it is preferable to make the lower connecting piece of iron pipe to which the straight glass lengths are joined by rubber tubes.

25 The Orifice Method can be used for measuring the very smallest as well as the very largest volumes of air occurring in practice. The velocity coefficient $f$ for well-shaped orifices such as shown in Fig. 3 when of 4 in. throat diameter ($D_1$) and over may safely be taken as 0.99.

26 Next to the Receiver Method, the Orifice Method is the most certain and the most reliable method for measuring air, and it is therefore generally recommended as the standard for the calibration of other air-measuring methods. A uniform rate of flow, however, is presupposed, as a pulsating flow, such as comes from reciprocating or positive-pressure compressors, cannot be measured reliably by any method which depends on a $\gamma V^2$ observation unless the discharge piping is extremely long sufficient to dampen out all pulsations.

### PITOT-TUBE METHOD

27 The Pitot Tube shown in Fig. 7 is used for measuring the velocity head in a transmission pipe. Essentially it consists of two tubes, one of which, $A$, passes straight into the service pipe to measure the static pressure, while the other tube, $B$, is made to point upstream to measure the sum of the static pressure plus the velocity head. The combination of these two tubes gives the velocity head alone as shown on the middle U-tube $C$ in Fig. 7. Equation [5] applies, $f$ being practically unity, $a$ being the pipe area, $p_2$ the static pressure, and $p_1 - p_2$ the differential reading. Since, to keep down friction losses, the velocity in the transmission pipe is usually very low, various artifices, such as an inclined tube, have to be resorted to, to get a reliable reading of $p_1 - p_2$. Also, the measurement of static pressure, unless special precautions are taken, is subject to serious error.

A good deal of work has been done in devising an instr ument to read correctly and not be subject to the common errors so often occasioned by improper installation of the pitot tubes. This has been reported from time to time before The American Society of Mechanical Engineers.

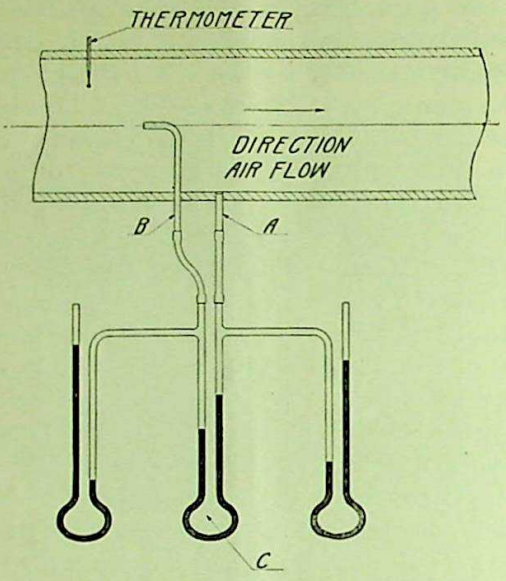


FIG. 7 PITOT TUBE, ELEMENTARY FORM

28 Fig. 8 illustrates a commercial flow meter on the pitot-tube principle embodying the latest ideas on the subject. For instance, the reading $p_1 - p_2$ is magnified as shown diagrammatically in Fig. 9

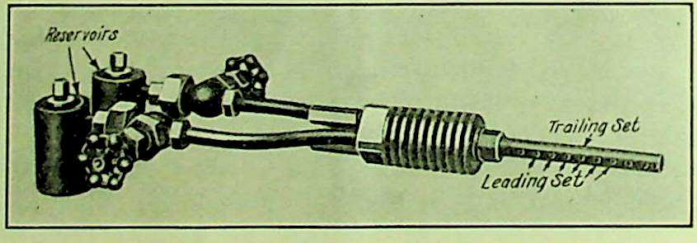


FIG. 8 NOZZLE PLUG OF AIR-FLOW METER WITH LEADING AND TRAILING OPENINGS

by having the static leg of the U-tube point downstream, so that the drag of the gas or fluid over the trailing opening lowers the pressure in that leg and thereby increases the differential reading in the U-tube

corresponding to the given velocity. Also the impact pressure and the static pressure are obtained more accurately by means of a nozzle plug as shown in Fig. 8 inserted in the service pipe. The single leading and the single trailing opening shown in Fig. 9 are here replaced by a leading set of openings extending approximately across the diameter of the pipe, while the trailing set of openings is located

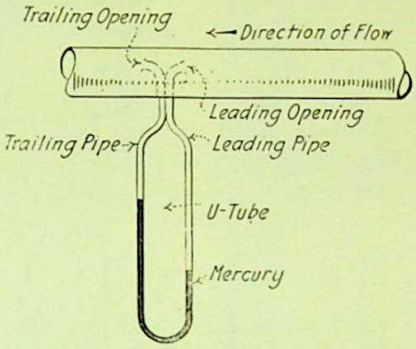


FIG. 9 DIAGRAMMATIC ILLUSTRATION OF NOZZLE PLUG AS USED IN FLOW METER OF FIG. 8

midway between the ends of the tube at the center of the pipe diameter, and faces in the direction of the flow. The introduction of the nozzle plug in the pipe line causes no appreciable drop in the pressure even at very high rates of flow.

### VENTURI METHOD

29 The Venturi Meter shown diagrammatically in Fig. 10 consists essentially of a direct and a reversed nozzle placed throat to throat, making a common throat. In general, two U-tubes $B$ and $D$ or the equivalent, are necessary, one to give the static pressure $B$ in the throat and the other to give the pressure drop $D$ from the main pipe, or high-pressure region, to the throat. It will be noticed that the impact tube $A$ points upstream, so as to include whatever velocity head may exist in the main pipe. After the air passes the throat, the pressure rises again to nearly, but not quite, its original value. This may be demonstrated by the use of impact tube $C$, pointing upstream, in the pipe beyond the throat. U-tube $F$ communicating with both impact tubes $A$ and $C$ will give directly the pressure loss caused by the insertion of the venturi meter into the system.

30 The direct nozzle should be short and well rounded, while the reversed nozzle should be well tapered with a half angle of about

4 deg. The inside of the meter must be smoothly finished, and particular care must be taken at the entrance of the U-tube into the throat of the meter to avoid all burrs and roughness. Also the impact tube in the main pipe should be small to avoid any eddies and disturbances due to the introduction of the impact tube.

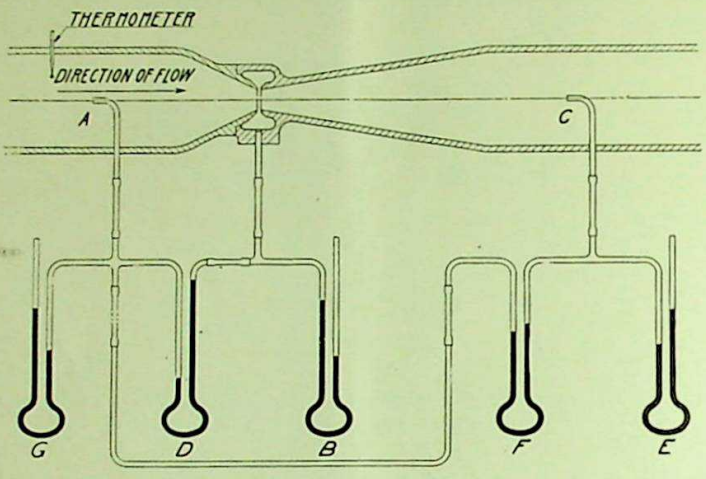


FIG. 10 VENTURI METER

Readings on U-tubes *B* and *D* and of the barometer are necessary

31 The quantity of air may be computed by Eq. [5]. As the U-tubes are generally used with mercury, it is convenient to write Eq. [5] in the following form:

$$Q = 423\,fa\,\frac{1}{\sqrt{T_1}}\,\sqrt{P_2\,(P_1 - P_2) - 0.0665\,(P_1 - P_2)^2} \quad \ldots\ldots [6]$$

where

$Q$ = cu. ft. of standard air (14.70 barom. and 60 deg. fahr.) per min.
$T_1$ = absolute temperature in main pipe in deg. fahr.
$f$ = velocity coefficient of throat, usually between 0.95 and 0.99
$a$ = area of throat in square inches
$P_1$ = absolute initial (high) pressure in inches Hg
$P_2$ = absolute pressure in throat in inches Hg
$P_1 - P_2$ = pressure drop.

32 In designing a venturi meter for a particular case, the area $a$ is so chosen that the value of $P_1 - P_2$ for the quantity of air most commonly used should be large enough to be read conveniently

and with reasonable accuracy and yet not so large as to cause an excessive pressure drop and power loss in the meter.

33 It is preferable to measure the air before it is compressed, so that $P_1$ and $T_1$ are the atmospheric pressure and absolute atmospheric temperature, respectively. A single U-tube like U-tube $B$ in Fig. 10 is then sufficient. The actual pressure $P_1$ must be obtained from the existing barometer and then $P_2$ can be computed from the reading $P_1 - P_2$ on the U-tube.

34 The U-tube can also be calibrated in cubic feet of air per minute instead of indicating only inches of mercury pressure. When so calibrated it can only refer to some standard or average condition of air, and any change in temperature, barometer or humidity will affect the correct reading on such a calibrated scale.

## IMPACT FLOAT METHOD

35 The Impact Float Method described previously in a paper by Mr. R. H. Rice before this Society and illustrated in Fig. 11 consists in allowing the air to be metered to impinge on a float $F$, usually in the form of a disk, suspended vertically in a cone. The air enters the small end of the cone and its velocity is steadily reduced as it passes up toward the larger end of the cone. The force tending to lift the float, and whatever is attached to it, against gravity consists partly of the direct impact of a part of the air against the float, and partly of the pressure drop caused by the passage of the air through the annulus between the float and the cone in a sort of *vena contracta*. As the float rises in the cone, this force is reduced by the lowered velocity of the air, so that the position of the float in the cone is a function of the quantity of air passing through the cone.

36 It is desirable, however, for reasons which will appear later in connection with air regulation, to confine the position of the float within narrow limits, regardless of the quantity of air. This is accomplished as shown in Fig. 11 by connecting the float to a horizontal lever or beam $B$, the force on the float being balanced by a sliding weight $W$, which can be moved to any part of the beam. The beam is so graduated that the position of the sliding weight on it gives directly the volume of the air entering the cone.

37 The impact on the float or the momentum of the air is evidently $mV$, where $m$ is the mass of air impinging on the float per second and $V$ is its velocity. Since for a constant cross-section, $m$ is proportional to $\gamma V$, where $\gamma$ is density of the air, the impact on

the float is proportional to $\gamma V^2$ or to $\frac{m^2}{\gamma}$. Similarly, the pressure drop through the annulus around the float is $\gamma \frac{V^2}{2g}$, where $V$ is now the velocity in the annulus, and is therefore also proportional to $\frac{m^2}{\gamma}$.

38 When the air flows through the annulus between the float and cone a *vena contracta* obtains whose area varies with each volume of air flowing. On account of this, formulæ for the float force or

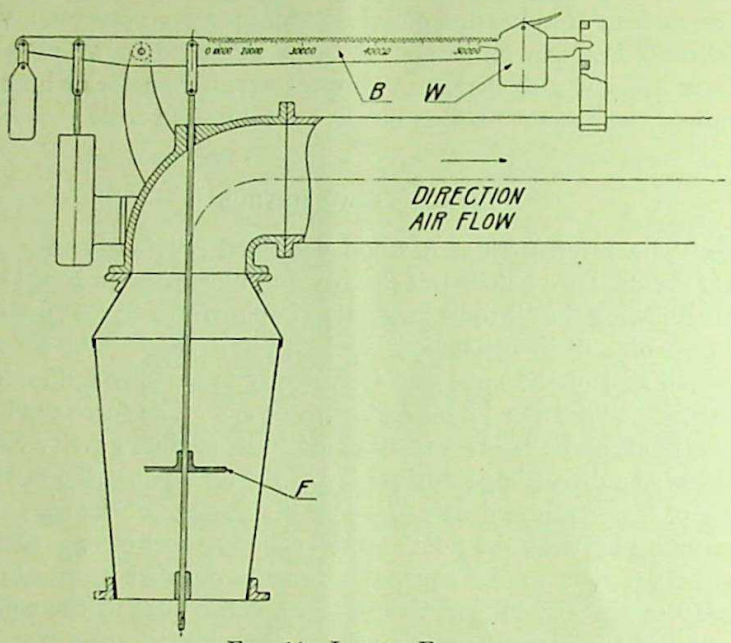


FIG. 11 IMPACT FLOAT
Air meter

reaction based on purely mathematical deductions require modification based on experimental results. The slope of the cone and the ratio of float diameter to cone diameter and also the average velocity of the air through the cone influence the value of this float force. For long cones having a slope of about one inch in five inches and with floats having areas between 50 per cent and 95 per cent of the annulus area and using average velocities through the cone under 100 ft. per sec., the following formula found experimentally will hold:

$$F = 9 \times 10^{-4} Q^2 \gamma \sqrt{\frac{A}{a^3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots [7]$$

in which

$F$ = total force of float in lb.
$Q$ = cu. ft. of air per min.
$\gamma$ = density of the air in lb. per cu. ft.
$A$ = float area in sq. ft.
$a$ = annulus area in sq. ft.

39 The upward moment of the force $F$ about the fulcrum of the beam (Fig. 11) is counterbalanced partly by the downward moment of the weight of the float and partly by the moment of the sliding weight, which is downward but may be upward for small volumes of air. In any case, however, the system may be reduced to one having a weightless float and beam, so that the upward moment of the float force $F$ is balanced by the downward moment of the sliding weight $W$. Since both the weight $W$ and the lever arm of $F$ are fixed, the lever arm of $W$ must be always proportional to the force $F$, or to $\frac{M^2}{\gamma}$, in which $M$ is $Q$ referred to standard conditions of barometer, temperature and humidity, and therefore represents a definite weight of air.

40 In other words, the beam must have a quadratic scale; that is, the longitudinal distance of the sliding weight from the zero on the beam is four times as great for 20,000 cu. ft. and nine times as great for 30,000 cu. ft. as it is for 10,000 cu. ft. The graduations on the beam are made correct for the average atmospheric conditions of the air at the place where the instrument is to be used.

41 In metering the air all that is necessary after the beam is calibrated is to move the sliding weight $W$ along the beam until the beam is level, exactly as in the case of the beam on a pair of beam scales. The pointer on the weight $W$ then indicates the amount of air flowing.

### CONSTANT-VOLUME GOVERNING

42 Of the above-mentioned methods of measuring air in general, only the last two, the Venturi Meter and the Impact Float, are commercially used for regulating the supply of air to blast furnaces. With the advent of the centrifugal compressor a blowing apparatus became available which could be very nicely regulated in respect to holding any constant volume of air supply to the furnace. The centrifugal compressor delivers an absolutely steady stream of air without any pulsations whatever and the pressure delivered by such a unit varies closely with the square of its speed. Hence, any volume

regulation of air need only influence the speed of the driver of the centrifugal compressor. Up to a very short time ago all volume regulation for centrifugal compressors was based upon a calibrated scale for some standard condition of air, usually assumed as dry air at the average temperature and barometer existing at the location of the set. We again emphasize here the fact that constant-volume governing is referred to, whereas the object desired is to introduce a constant *weight* of oxygen into the furnace.

43 The governing of a centrifugal compressor, in order to hold constant volume, requires the use, first, of a meter for measuring the volume of air flow. The necessary qualifications of such a meter, taking into consideration the large quantities of air used in blast-furnace operation, are: (1) It must not waste any of the air it meters; (2) The power consumed in the metering and governing processes must be small, which makes it necessary that the friction losses of air flow through the meter be small; (3) The governor must be sensitive so that a small change in the quantity of air supplied will be sufficient to actuate the governor.

### THE MULTIPLE VENTURI METER

44 An ordinary venturi meter in which the entire quantity of air flowing must be drawn through a sufficiently small throat to give a suitable drop of pressure would involve considerable power loss. To reduce this power loss a multiple venturi has been devised, consisting of a number of concentric venturis. Referring to Fig. 12, which shows a multiple venturi, a very small part of the total air flow passes through the small or inner venturi. At the throat of this small venturi the largest pressure drop is obtained. A larger quantity of air flows around the inner venturi and through the second venturi, but the bulk of the air flow is around the second and through the third or outer venturi.

45 Consider a flow of 45,000 cu. ft. of standard air per minute through the triple venturi shown in Fig. 12, the air flowing from right to left as indicated. The air at inlet to the venturi is assumed to be at practically atmospheric pressure and temperature. By the use of Equation [6] and by assuming a probable velocity coefficient $f = 0.95$ for the inner venturi and $f = 0.85$ for the two outer venturis, we can show that the following conditions obtain. Through the inner venturi 175.8 cu. ft. of standard air flows. The pressure at the throat is 22.65 in. Hg, representing a drop of pressure of 7.28 in. Hg. About 1777 cu. ft. of standard air per minute flows through

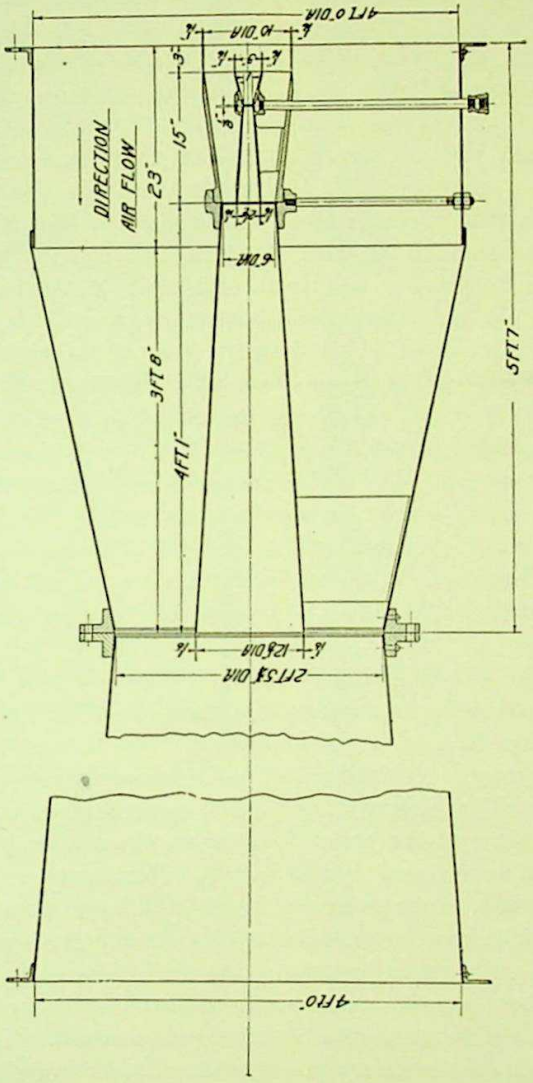


FIG. 12 TRIPLE VENTURI METER

Used for securing a reasonable drop of pressure without excessive power loss

the middle venturi. The drop of pressure from atmosphere (29.93 in. Hg) to the throat of this venturi is 0.73 in. Hg. All the remaining air (43,047 cu. ft.) passes through the outer or third venturi, and the drop of pressure from atmosphere to the throat of this venturi is 0.69 in. Hg.

46 The loss of power in metering the air through this triple venturi, when passing 45,000 cu. ft. of standard air per minute, can be determined from the loss of pressure between that existing at the entrance to each venturi and the pressure existing at the exit or discharge end of each venturi, taking into account the volume of standard air passing through each. This gives a loss of power of 0.18 hp. for the smaller or inner venturi, 1.06 hp. for the middle venturi and 31.38 hp. for the outer or largest venturi, making a total power loss through the entire triple venturi of 32.62 hp.

47 The largest drop of pressure in this triple venturi meter occurs in the throat of the inner or smallest venturi. With a flow of 45,000 cu. ft. of standard air per minute, the calculated drop is 7.28 in. Hg (3.57 lb. per sq. in.) pressure. With air entering the meter from atmosphere the throat pressure will be negative (suction). With varying flow of air through the venturi the suction at the throat of the inner venturi will also vary; and this varying suction can be used for governing the driver of a centrifugal compressor so as to hold a definite "*constant volume*" of air flow per minute.

### THE VENTURI METER CONSTANT-VOLUME GOVERNOR

48 Fig. 13 shows in a somewhat diagrammatical manner a means for accomplishing this. The pipe leading from the throat of the inner venturi meter is connected to part *A* representing a mercury-sealed pressure bell, or mercury pot. Suction pressure at the venturi throat is established in the space *B* between the stationary part of the pot and the upper and movable bell. Variations of pressure in *B* cause this bell to move up or down. The suction pressure is sealed from atmosphere by a column of mercury surrounding the long sheet-steel skirt or extension of the bell. There is sufficient clearance space between this sheet-steel skirt and the inner and outer shell surrounding it to prevent any frictional contact. The movement of the bell in the mercury pot is transmitted through the links *C*, *D*, and *E* to the steam-valve control to the turbine, thereby opening and closing the number of valves admitting steam to the turbine. An adjustable spring *F* can be set so as to counterbalance the pull of the bell for any desired volume of air. Handwheels *G* are used for

setting the spring tension, as can be readily understood from the figure. Dashpot *H* dampens out the oscillations of this gear.

49 The method of setting for regulation is as follows: Having determined exactly the number of cubic feet of standard air desired per minute, the operator turns the handwheel *G* and observes the height of the registering mercury column also attached to the pipe leading from the throat of the inner venturi. This mercury column is not only inscribed in inches of mercury, but is also calibrated in cubic

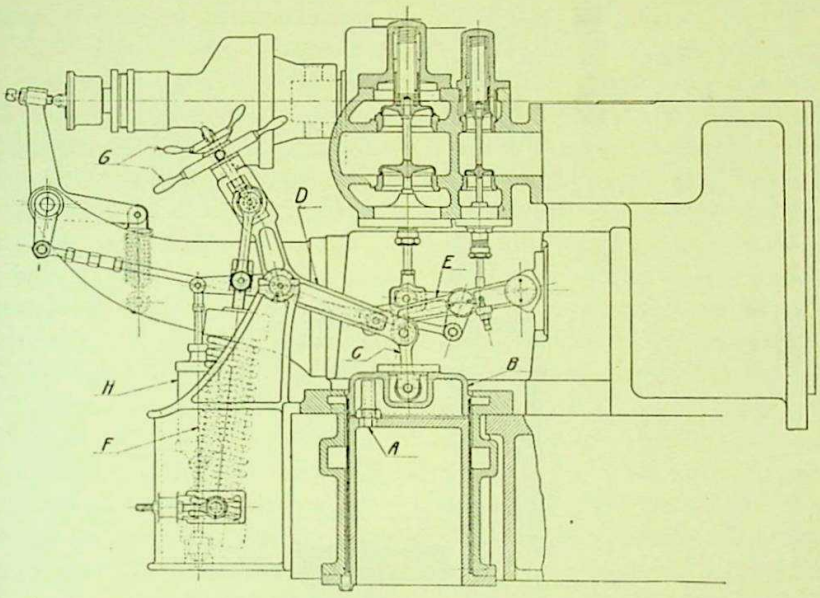


FIG. 13 CONSTANT-VOLUME GOVERNOR FOR VENTURI METER

Uses a mercury pot subjected to the pressure of the throat of the venturi meter shown in Fig. 12 and with adjustments so that it can hold any desired volume as indicated on a calibrated mercury tube shown in Fig. 14

feet of air per minute, as shown in Fig. 14.[1] When the mercury column registers the desired number of cubic feet of standard air per minute, handwheel *G* is locked. Any change in air flow through the venturi will change the suction in the pipe leading from the throat of the inner venturi to the mercury pot shown in Fig. 13 and also to the gage in Fig. 14. A change of suction on the mercury pot, however, influences the governing mechanism so as to increase the steam ad-

[1] For Figs. 12, 13 and 14 the author is indebted to the Southwark Foundry and Machine Company.

mission to the turbine when the suction decreases, or decrease the steam admission to the turbine when the suction increases. By this means constant-volume governing is obtained. Increasing the steam admission to the turbine speeds up the unit, thereby increasing the discharge pressure of the compressor, and vice versa. Equilibrium must be established between the spring tension set by handwheel

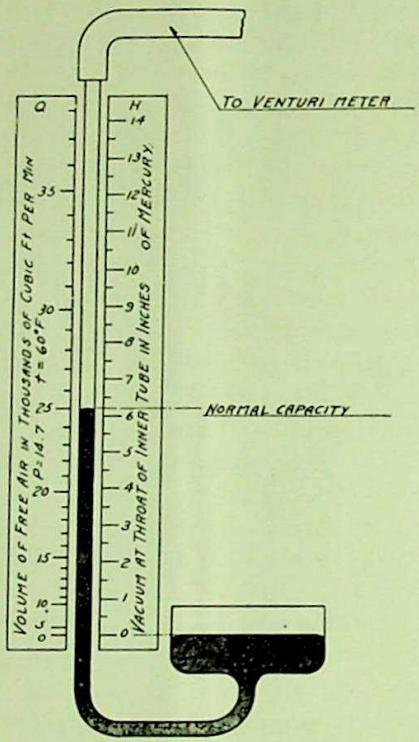
TO VENTURI METER
Q
VOLUME OF FREE AIR IN THOUSANDS OF CUBIC FT PER MIN
t = 60°F
P = 14.7
H
VACUUM AT THROAT OF INNER TUBE IN INCHES OF MERCURY
NORMAL CAPACITY

FIG. 14 U-TUBE AND QUANTITY SCALE FOR VENTURI METER

Used with a venturi meter as shown in Fig. 12 and with a constant-volume governor as shown in Fig. 13

*G* and the pressure in the confined space in the mercury pot before the governing mechanism comes to rest.

50 The calibration of mercury column indicating number of cubic feet of air per minute refers to standard air, that is, air of the average temperature and barometer and humidity for which the unit has been calibrated. Fig. 14 shows a calibrated scale for a normal capacity of 25,000 cu. ft. of air per min., whereas Fig. 12 shows a multiple venturi of a much greater normal capacity, probably 40,000 cu. ft. per min.

## THE IMPACT FLOAT CONSTANT-VOLUME GOVERNOR

51 The second method for regulating turbo-compressors for blast-furnace work involves the use of the impact float which was originally conceived as part of the means for constant-volume governing. Fig. 11 shows the impact float suspended in a conical pipe and attached to a beam calibrated in cubic feet of air per minute. If this beam were attached by linkages to the governing mechanisms of the driver of a centrifugal compressor it could be made to take care of its governing.

52 Fig. 15 shows such a constant-volume governor. Float *F* is suspended by a vertical rod from beam *B*. The float is made so it can be heated with a small amount of compressed air introduced through the hollow suspension rod *S* so as to prevent moisture from condensing and freezing upon the float in winter. The beam is fulcrumed at *A* and is balanced by counterweight *C* and movable sliding weight *W*. Dashpot *D* prevents too rapid movements or oscillations. Handwheel *H* on one end of the beam moves the sliding weight *W* longitudinally along the beam by means of a threaded shaft and nut. The sliding weight can thus be set at any definite position indicating the desired volume of air per minute. Any movement of the beam is transmitted through linkages *M*, *N*, *O* and *T* to a controlling pilot valve *V* which will admit steam or oil under pressure to either one or the other side of a piston *P*. This piston is connected directly to a nest of controlling valves which admit steam to separate groups of turbine nozzles. The turbine governor *G* is used as a speed-limiting device, so arranged that when the turbine reaches a speed corresponding to that at which the compressor would deliver the maximum permissible pressure (for blast-furnace work usually 30 lb. per sq. in. gage), it moves linkages *L*, *K*, and *N* and thereby influences the governing pilot valve from opening more valves for steam admission. In other words, at this speed it takes the control of the turbine out of the hands of the constant-volume governor.

53 The important feature of this method of constant-volume governing is the very small pressure drop involved by the air passing through the conical pipe of the meter. The area of the float is so large that a very low velocity of air and an extremely small pressure difference on the two sides of the float is sufficient to afford all the force necessary to move the entire governing mechanism. This fact also makes the governor sensitive to the smallest variation in the quantity of air passing through the compressor.

54 The force exerted upon the impact float when used as a constant-volume governor can be determined from Equation [7] previously given.

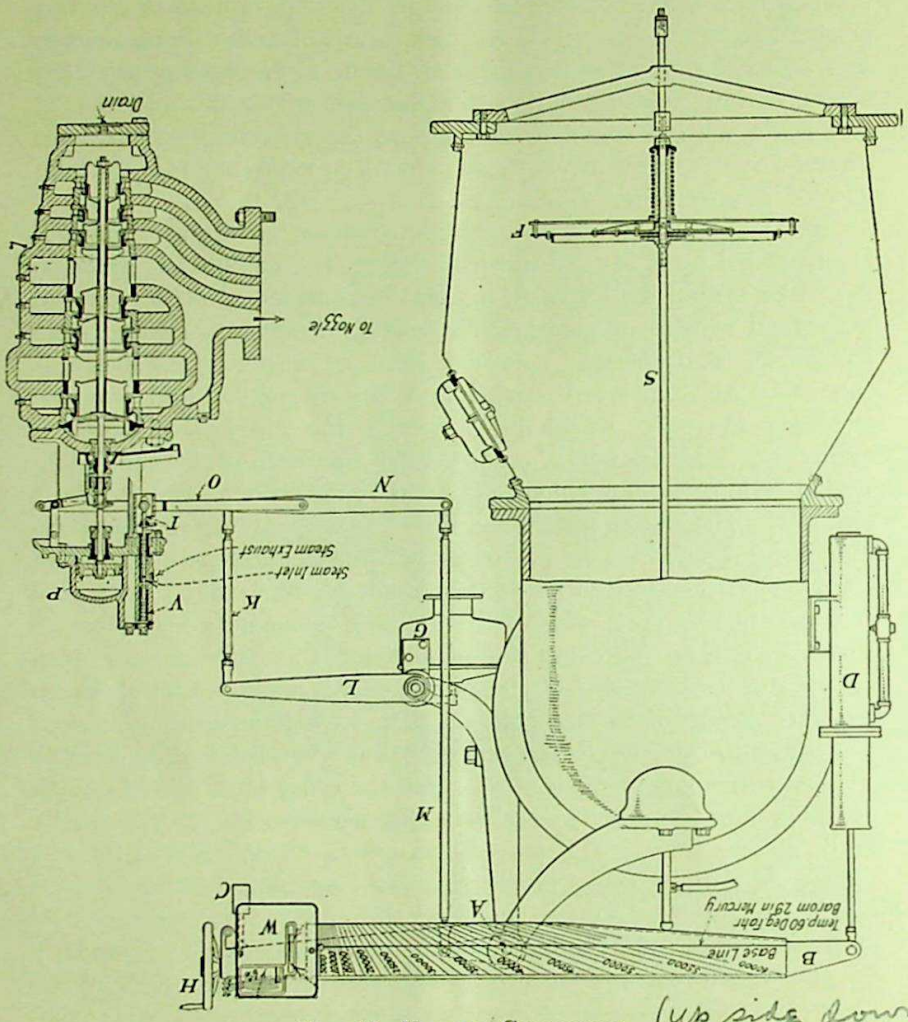


FIG. 15 VOLUME CORRECTOR

Shown mounted on the beam of a constant-volume governor

55 It has been found advisable to make the area of such a float equal to

$$A = 700 \frac{Q_1^3}{Q} \frac{1}{\sqrt{p^3 \gamma}} \quad \ldots\ldots\ldots\ldots\ldots\ldots [8]$$

in which

$A$ = area of float in sq. ft.
$Q$ = correct quantity of cu. ft. of standard air per minute for a definite position of sliding weight
$Q_1 = Q + q$
$q$ = smallest change of volume in cu. ft. of air per min. desired to produce an effect governing
$\gamma$ = density of air in lb. per cu. ft.
$p$ = mean effective pressure in lb. per sq. in. for which the compressor has been designed.

56 It will be noticed that the smaller the value of $q$, the more sensitive will be the governing and the smaller will be the force available for governing purposes. If $q$ is taken reasonably large the governing forces become greater but the constant-volume governor will be less sensitive. In other words, $q$ is a measure of the per cent of the regulation desired.

57 When the float is in proper position for the compressor to deliver its normal rating of air against the normal pressure, the annulus area between the float and the cone may be found from the following equation:

$$a = 0.0017\, Q \sqrt{\frac{\gamma}{P_m}} \qquad [9]$$

in which

$a$ = annulus area in sq. ft.
$Q$ = the normal rating of the compressor in cu.ft. of air per min.
$P_m$ = the mean effective pressure corresponding to the normal pressure rating in lb. per sq. in.
$\gamma$ = density of air in lb. per cu. ft.

58 It is advisable to make the inlet pipe diameter for supplying atmospheric air to the constant-volume governor and hence to the compressor of such diameter as to limit the velocity of air to approximately 30 ft. per sec. The constant-volume-governor cone should extend into an inlet box which would admit air with uniform distribution into the cone. It is therefore advisable to have the inlet box as large as possible.

59 Table 1 gives an idea of the float forces and float areas employed in practice, the float force having been measured experimentally in each case.

TABLE 1 FLOAT AREAS AND FORCES USED IN IMPACT FLOAT METHOD

| Normal rating of unit, cu ft. of standard air per min. | Quantity of air delivered, cu. ft. per min. | Float area, sq. ft. | Float force, lb. |
|---|---|---|---|
| 50,000 | 45,000 | 7.43 | 168 |
| 40,000 | 40,000<br>35,000 | 6.87 | 167<br>128 |
| 30,000 | 30,000<br>25,000 | 4.90 | 171<br>118 |
| 20,000 | 22,500<br>20,000<br>18,300 | 3.14 | 112<br>89<br>75 |

INACCURACIES OF CONSTANT-VOLUME GOVERNORS

60 Both the venturi meter and the impact float methods of constant-volume governing applied to centrifugal compressors have resulted in improving the regulation of blast furnaces. Unfortunately, this means of regulating cannot be applied to any other type of air-compressing machinery because all other known types of compressors do not produce an absolutely steady flow of air. The advent of constant-volume governing has eliminated the only remaining guesswork heretofore employed in regulating the air supply to a blast furnace. With careful analysis of the iron ore and coke charged to the furnace and a careful weighing of them as they are charged, the amount of oxygen necessary for combustion of the coke and reduction of the iron ore is accurately and easily determined. It is then only necessary in the venturi method to adjust the governing mechanism so that the indicating mercury column shows the desired quantity of atmospheric air per minute; or, in the impact float method, merely to set the sliding weight on the governing beam to the indicated quantity of atmospheric air desired. In the latter case the weight can be set immediately and the governor will automatically establish the proper air flow, whereas, in the former case adjustment must be made slowly until the desired air flow is obtained. In both cases, however, if the atmospheric conditions of the inlet air changes from the so-called standard or average conditions for which the governors were calibrated, the actual quantity of air delivered, or more correctly, the actual *weight* of oxygen sent to the blast furnace, will vary. This variation may be considerable.

61 For instance, if the standard air conditions are taken as dry air at 60 deg. fahr. and 29 in. Hg and the governor is calibrated for these conditions, it is possible to conceive a summer condition of 100 deg. fahr. with a barometer of 26 in. and fully saturated air (as on a rainy and stormy day). There is 14 per cent less oxygen per cubic foot of air under these conditions than under standard conditions. In winter, atmospheric air may be at 0 deg. fahr., the air perfectly dry and a barometer of 30 in. Hg. A cubic foot of this air will contain 8 per cent more oxygen than the standard air. It is, therefore, perfectly possible to supply from 8 per cent too much oxygen to 14 per cent too little oxygen to the blast furnace, if regulation is dependent on constant-volume-governor settings of standard or average conditions of atmospheric air.

## THE VOLUME CORRECTOR

62 The main object of this paper is to describe a new instrument named a volume corrector which can be applied to the sliding weight and calibrated scale of an impact-float constant-volume governor for correcting this governor when handling air of any temperature, barometer or humidity. An instrument similar in principle and somewhat similar in construction can also be applied to the indicating mercury column of the venturi meter so as to obtain proper volume correction.

63 The volume corrector applied to the impact-float constant-volume governor is shown in Fig. 15. The scale beam $B$, instead of having vertical calibration lines for standard conditions of air, has sloping constant-volume lines engraved upon it. The volume corrector proper is mounted on the front of the sliding weight $W$. Fig. 16 is a photographic view of a part of this scale beam with volume corrector mounted on the sliding weight; and Fig. 17 is the same with the hinged door of the volume corrector open, as is the case when the instrument is to be set.

64 Fig. 18 shows a little more clearly the arrangement of this instrument. There are three milled heads, $A$, $B$, and $C$, provided for adjusting pointers indicating barometer, temperature and humidity. All that is required of the operator is to set these pointers correctly. After obtaining the actual barometer reading from a standard barometer, and the actual temperature of the incoming air, and observing the existing humidity — which is usually done by noting the temperature difference between a wet- and dry-bulb thermometer, pointer $a$ is set at the proper barometric reading, pointer $b$ at the

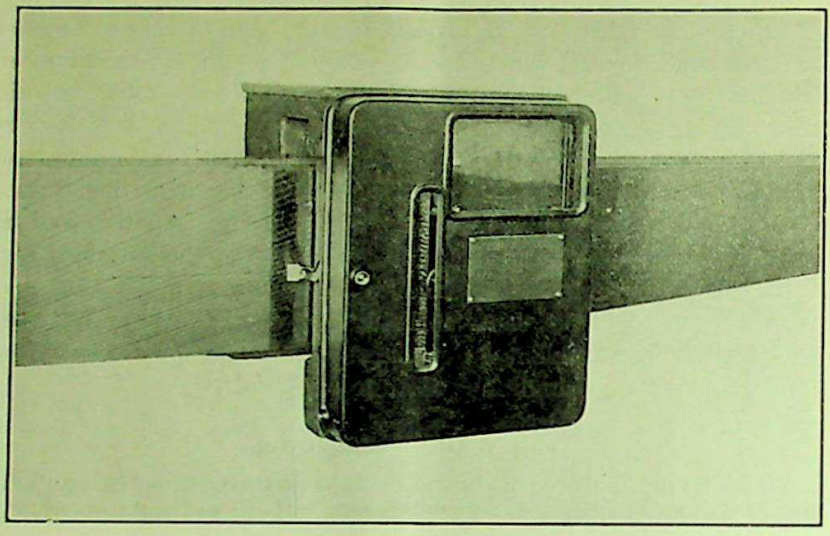

FIG. 16 PHOTOGRAPHIC VIEW OF THE VOLUME CORRECTOR
Front door of casing closed

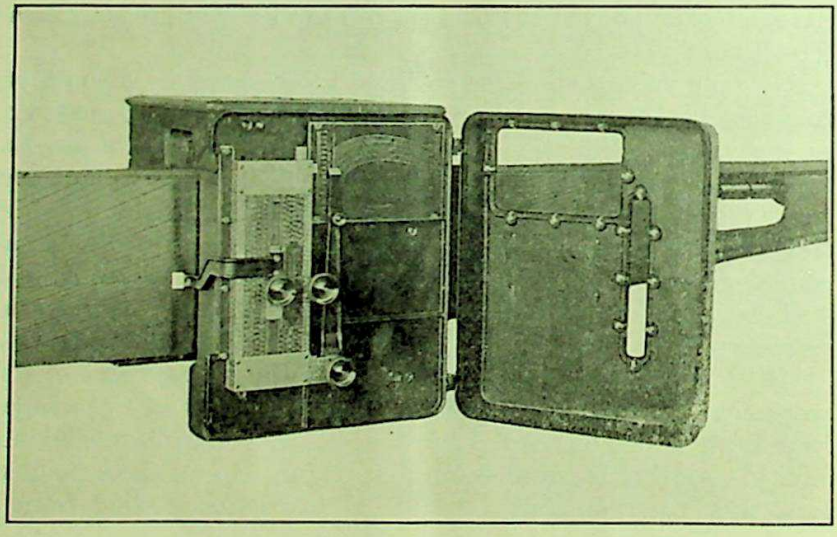

FIG. 17 PHOTOGRAPHIC VIEW OF VOLUME CORRECTOR
Front door of casing opened

proper temperature reading, and pointer *c* moved so as to intersect the curve corresponding to the observed temperature difference between the wet- and dry-bulb thermometers.

65 The movement of each of these pointers influences the final position of the main pointer *P*. This main pointer moves in a vertical direction with respect to the scale on the beam. After the volume corrector is properly set, the sliding weight to which the volume corrector is permanently attached is moved horizontally along the

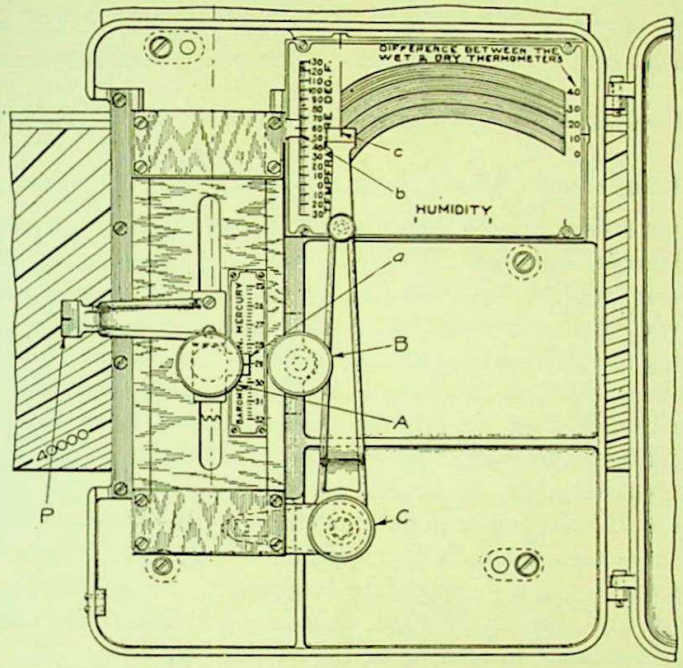


FIG. 18 VIEW OF VOLUME CORRECTOR SHOWING DETAILS

beam until the main pointer *P* intersects the sloping line on the graduated scale designating the proper volume of standard air required. When so set the sliding weight is in the proper position. This permits corrections to be made for variation in temperature, barometer and humidity so that a constant *weight* of oxygen is supplied no matter what the conditions of the atmospheric air. Having determined that the blast furnace requires a definite volume of standard air (dry air at 60 deg. fahr. and 29 in. Hg), the governor with corrected setting of the sliding weight will deliver the proper amount of

actual air which would contain the same *weight* of oxygen as would be contained in the required quantity of standard air.

66 The amount of oxygen in dry air varies directly as the density of the air. The density of air is directly proportional to the barometric pressure and inversely proportional to the absolute temperature. Expressed symbolically, $\gamma \propto \frac{B}{T}$. As the float force is proportional to $\frac{M^2}{\gamma}$, a change in density $\gamma$ with the governor set to maintain a constant weight $M$ of air per second will cause the governor to change the speed of the compressor until a new weight $M_1$ is delivered, such that the new value of $\frac{M_1^2}{\gamma_1}$ is the same as the original value of $\frac{M^2}{\gamma}$. Expressed symbolically, for a given setting of the sliding weight, $M^2 \propto \gamma$, or $M \propto \sqrt{\gamma} \propto \sqrt{\frac{B}{T}}$. For moist air the barometer no longer represents the pressure of the air itself, for part of the barometric pressure is due to the vapor pressure in the air. This vapor pressure must therefore be subtracted from the observed barometric pressure in order to get the net air pressure to be used in computing the air density and hence the weight of oxygen per cu. ft. of air. For saturated air (a relative humidity of 100 per cent) the vapor pressure can be read directly from steam tables for the observed atmospheric temperature. If the air is not quite saturated, the relative humidity, or the percentage of the possible maximum of moisture in the air, can be determined in a number of ways; usually, from a dry- and wet-bulb thermometer arrangement. The vapor pressure for a given temperature is proportional to the relative humidity, and this must then be subtracted from the observed barometric pressure in computing the air density.

67 The graduated scale on the beam of the constant-volume governor was designed by taking a horizontal base line such as was shown in Figs. 15, 16 and 17, and shown schematically in Fig. 19 as $AA'$, and placing thereon the proper calibration for standard air (dry, 60 deg. fahr., 29 in. Hg). The zero on this line gives the position of the sliding weight when the constant-volume governor beam is in equilibrium and no air is flowing. The point $B$ (Fig. 19) represents the position of the sliding weight for 10,000 cu. ft. flow; and point $C$ its position for 20,000 cu. ft. flow, etc. The distance $AC$ is made equal to four times $AB$. Similarly the distance $AD$, where $D$ represents the 30,000 cu. ft. point, is made equal to nine

times $AB$. With respect to temperature, the graduations on the $AA'$ hold good so long as the prevailing atmospheric temperature is 520 deg. fahr. absolute. When the prevailing temperature is other than 520 deg. fahr. absolute, the relations of the distances $AB$, $AC$, $AD$ to each other remain unchanged; but they must all be multiplied or foreshortened by the same ratio. This is accomplished in the following manner:

68 Referring to Fig. 19, let the line $OAB'$ be perpendicular to the base line $AA'$; and let $OA$ represent to some scale 520 deg. fahr. absolute, and $OB'$ represent 2080 deg. fahr. absolute to the same scale, so that $OB' = 4\,OA$. Draw $B'C'$ parallel to $AA'$ and $CC'$ parallel

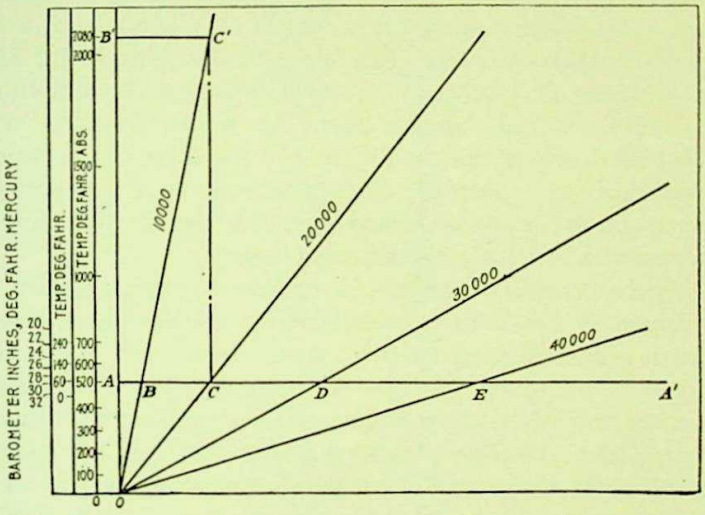


Fig. 19 Diagram Illustrating Construction of Scales on Volume Corrector

to $OB'$. Also prolong the straight line $OB$ until it intersects the line $B'C'$ in the point $P$ (not shown). The triangles $OAB$ and $OB'P$ being similar, $B'P : AB :: OB' : OA$; or $B'P = 4\ AB$. But $B'C' = AC = 4\ AB$. Therefore $B'P = B'C'$; or $P$ coincides with $C'$. In other words, the intersection $C'$ of the line $CC'$ with $B'C'$ is a point on the straight line $OB$.

69 Now in actual operation when the governor is set to deliver 20,000 cu. ft. of standard air per minute for a temperature of 520 deg. fahr. and should the actual temperature be four times as high, or 2080 deg. fahr. absolute, the governor will, as explained before, with the same setting of the sliding weight, regulate for only 10,000 cu.

ft. of standard air per minute, because the density of the air at 2080 deg. fahr. absolute is one-fourth of that at 520 deg. fahr. absolute. The pointer of the sliding weight must under those conditions then read 10,000 cu. ft. without the sliding weight itself being disturbed in any way. In the volume corrector this would be accomplished by pushing up the final pointer along a uniform temperature scale until it reads 2080 deg. fahr. absolute, because the pointer traveling upward would then, as proved above, just intersect the 10,000 cu. ft. line *OBC*. It will be noticed that all the sloping lines representing definite volumes of air per minute meet at *C*. This would represent the point of absolute zero if the same temperature scale was carried down on the prolongation of the line *AB*. From the above it can be seen that if the volume corrector be made to carry a temperature scale with the same distances as employed in the engraving of the scale on the beam, and the main pointer *P* of the volume corrector be made to move vertically up and down the proper distance to this scale, the sliding weight can be set for any observed temperature of atmospheric air so as to deliver the proper volume of air containing the same weight of oxygen as is contained in the previously calculated necessary volume of air of standard conditions.

70 Further consideration will show that as far as the density or the square of the volume is concerned, doubling the absolute temperature is equivalent to halving the barometer. In other words, any barometric change can be expressed by an equivalent temperature change. For instance, if 29 in. Hg is taken as the standard barometer and 60 deg. fahr. (520 deg. absolute) as the standard temperature, a change to 28 in. barometer, the temperature remaining at 60 deg. fahr., is equivalent to a change to a temperature of $\frac{29 \times 520}{28}$ or 538.6 deg. fahr. absolute (78.6 deg. fahr.) with the barometer remaining at 29 in. Hg. The distance on the barometer scale from 29 in. to 28 in. must, therefore, equal the distance from 60 deg. fahr. to 78.6 deg. fahr. on the thermometer scale, whereas the correction necessary from 29 in. Hg to 25 in. Hg barometer is equivalent to a change to a temperature of $\frac{29 \times 520}{25}$ or 603.2 deg. fahr. absolute (143.2 deg. fahr.) with the barometer remaining at 29 in. Hg. The distance on the barometer scale from 29 in. to 25 in. must therefore equal the distance from 60 deg. fahr. to 143.2 deg. fahr.

71 The barometric scale constructed on the above principle for the volume corrector is evidently a reverse and reciprocal (that is,

non-uniform) scale. For constructional reasons, and chiefly to take care of humidity corrections explained later, it is desirable to have this scale uniform without affecting in any way the accuracy of the instrument. This is accomplished in the following manner.

72 Referring to Fig. 20, which gives a view of the volume corrector shown in Fig. 18 but with some of the front cover plate removed, $A$, $B$ and $C$ are the pins to which the milled heads $A$, $B$ and $C$ of Fig. 18 are attached. The main pointer in Fig. 18 is moved up and down in a vertical slot by means of pin $p$ in Fig. 20. When the

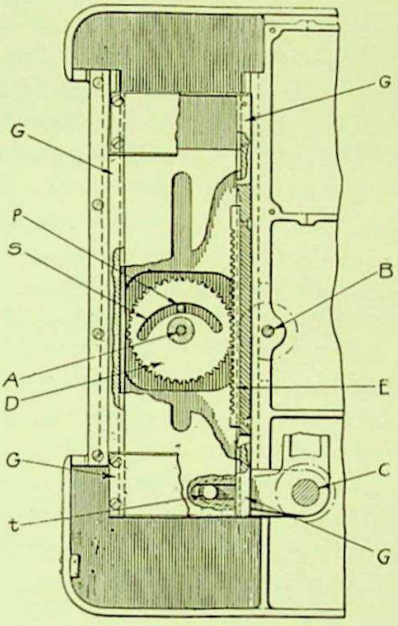


FIG. 20 SECTIONAL VIEW OF VOLUME CORRECTOR

operator moves milled head $A$ so that pointer $a$ indicates the barometer reading, gearwheel $D$ (Fig. 20) rotates about pin $A$ because it is meshed into a rack $E$ which remains stationary. Motion is given to pin $p$ (which is held in a vertical slot) by the slot $S$ in gearwheel $D$. This slot is in the form of a cam and so designed that pin $p$, and therefore the main pointer $P$, moves the proper distance vertically. The main pointer will move a less distance vertically when barometer pointer moves from 32 in. to 31 in. than it will when moving from 31 in. to 30 in., and less from 31 in. to 30 in. than it will from 30 in. to 29 in. Therefore, although the barometer

scale over which pointer *A* moves has uniform divisions, the actual vertical distance through which the main pointer *P* moves is non-uniform and follows a reciprocal scale.

73 The setting of temperature is accomplished through milled head *B* which is attached to a plate movable vertically between gibs *GG* and which carries with it the rack *E*, gearwheel *D*, and pin *p* with main pointer *P*. Moving *B* up and down does not revolve gearwheel *D* at all (that is, does not disturb the barometer setting), but simply moves main pointer *P* over a temperature scale shown in Fig. 18. Pointer *b* is set opposite the proper temperature reading.

74 The corrections for humidity in the volume corrector are based upon the following considerations: The barometric-pressure reading as usually observed is equal to the sum of the air pressure plus the vapor pressure. If the air is saturated, that is, if it contains all the water vapor it is capable of holding without precipitation at the particular temperature, the value of the vapor pressure at the given temperature can be ascertained experimentally or taken from the steam tables. If the degree of saturation or the relative humidity is, say, only 20 per cent or 50 per cent, then the vapor pressure as determined experimentally must be multiplied by 0.20 or 0.50 as the case may be.

75 The most usual method of ascertaining the relative humidity of the air is by means of a wet- and dry-bulb thermometer arrangement. In its simplest form it consists of two similar thermometers, the bulb of one of which is covered by a wet piece of sponge. If the air is fully saturated no evaporation into it can take place and the two thermometers record the same temperature. When the air is only partly saturated, the evaporation from the wet bulb lowers the thermometer reading; so that the difference in the readings of the wet and dry thermometers can be taken as a measure of the relative humidity of the air. For any combination of relative humidity and atmospheric temperature the vapor pressure is a definite quantity. This vapor pressure must be subtracted from the observed barometer reading in order to give the net or correct air pressure to be used on the barometer scale above described; since it is the density (and therefore the actual pressure) of the air alone that is of importance, and not the density of the mixture of air and water vapor.

76 It is important to note that the humidity correction in pounds per square inch or in inches of mercury is independent of the actual barometer reading, and depends only on the atmospheric temperature and on the difference between the wet- and dry-bulb ther-

mometer readings (relative humidity). The humidity correction can therefore be made mechanically if the pointer $P$ on the sliding weight is given an additional correction or movement which would be the equivalent amount of a certain subtraction of pressure on the barometric scale equal to the correction for the pressure due to vapor. It is for this reason that it is preferable to make the divisions on the barometric scale uniform, so that, for instance, a half-inch mercury correction would require the same movement no matter at what reading the barometer scale happened to be set. As will be shown later, the volume corrector accomplishes this, therefore no matter where the barometer pointer $a$ is set, the humidity correction moves the main pointer $P$ on the sliding weight the proper amount. It will also be noticed that the humidity is a function of the atmospheric temperature, that is, when the temperature is high the water vapor in the saturated air is higher than when the temperature is low. In the volume corrector the setting of the temperature pointer $b$ on the temperature scale automatically sets the humidity pointer $c$ to the correct temperature also.

77 Referring to Fig. 18, the correction for humidity is made by loosening milled head $C$ and swinging pointer $c$ until it intersects or indicates the proper amount of difference in reading between the wet- and dry-bulb thermometer. The movement of the long arm carrying pointer $c$ about the center of milled head $C$ moves pin $t$ attached to a plate carrying gearwheel $D$, but does not move rack $E$. Moving gearwheel $D$ vertically up or down rotates $D$ because $E$ is stationary and thereby moves the main pointer $P$ similarly, as heretofore described.

### ACCURATE CONSTANT-VOLUME GOVERNING

78 The volume corrector therefore is an instrument which can be set by an operator at the existing barometer, temperature and humidity of the atmospheric air and when so set will permit the setting of the sliding weight on the scale beam in a position so that the constant-volume governor will hold or deliver the correct volume of air which would contain the same weight of oxygen as would be contained in a certain predetermined and desired volume of standard air.

79 This means that the blast-furnace operator, knowing the chemical compositions of the coke and iron ore and the amounts charged to the furnace in a stated period of time, can determine the exact volume of standard air (dry, 60 deg. fahr., 29 in. Hg) which

will contain the proper amount of oxygen necessary for combustion of the coke and reduction of the iron ore in the blast furnace. He need not perform any mathematical calculations as to how much more or how much less air must be supplied when the atmospheric conditions are not those considered standard in order to be sure the blast furnace is receiving at all times its exact a nd necessary weight of oxygen.

80 The volume corrector needs resetting every time the operator notices any change in the barometer, temperature or difference between the wet- and dry-bulb thermometer reading in order to be sure of securing the most efficient regulation. The air conditions, however, do not vary rapidly and the practice of inserting in an engine-room log every half hour the steam pressure, r.p.m., vacuum and other information can easily be extended to include readings of the barometer, thermometer and wet- and dry-bulb instrument. Even with the front cover of the volume corrector closed, transparent places are provided which will permit any one checking or observing these settings. The need of a volume corrector is apparent from the fact that it is possible to have a variation of weight of oxygen delivered to a furnace of 5 to 10 per cent ordinarily and in extreme cases as high as 20 per cent as a result of variations in atmospheric-air conditions, especially as between winter and summer. The gains in quality and quantity of output of a blast furnace obtained even by the former methods of constant-volume governing without volume corrections will be still further improved by the use of constant-volume governing with proper volume corrections.